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SOLID STATE CLIPPER DIODES FOR HIGH POWER MODULATORS

Stephen Levy
John E. Creedon

ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

November 1978

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Abstract:

End-of-line solid state clipper diodes are essential to high power pulse modulators. These diodes are chosen to reduce the potentially damaging inverse network and switch voltages which occur when the load is less than the network impedance; especially when non-constant loads are encountered. The choice of the clipper diode stacks for a megawatt (MW) average power pulser resulted from a study of commercially available units. Destructive tests of available units gave a figure of merit of 300:1 for the maximum single shot 10 microsecond ~~(μs)~~ current pulse to diode rated average current. A 150 ampere (A) average current diode was chosen for the 20,000 A worst case expected in the MW pulser giving a current safety factor of better than 2:1. For the 40 kilovolt (kV) pulser operation at a 1.5:1 voltage safety factor required 60 of the 1.0 kV diodes in series. A snubber capacitor and resistor across each diode provided equal voltage division and transient turn-on protection. Transient response of the snubber protected diode stacks was modeled at low powers and later confirmed in actual MW pulser operation.

SOLID STATE CLIPPER DIODES FOR HIGH POWER MODULATORS

By

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Summary

End-of-line solid state clipper diodes are essential to high power pulse modulators. These diodes are chosen to reduce the potentially damaging inverse network and switch voltages which occur when the load is less than the network impedance; especially when non-constant loads are encountered. The choice of the clipper diode stacks for a megawatt (MW) average power pulser resulted from a study of commercially available units. Destructive tests of available units gave a figure of merit of 300:1 for the maximum single shot 10 microsecond (μs) current pulse to diode rated average current. A 150 ampere (A) average current diode was chosen for the 20,000 A worst case expected in the MW pulser giving a current safety factor of better than 2:1. For the 40 kilovolt (kV) pulser operation at a 1.5:1 voltage safety factor required 60 of the 1.0 kV diodes in series. A snubber capacitor and resistor across each diode provided equal voltage division and transient turn-on protection. Transient response of the snubber protected diode stacks was modeled at low powers and later confirmed in actual MW pulser operation.

Introduction

High power line-type modulators require end-of-line clippers to protect circuit components from overvoltages due to short circuits in the load. The major components susceptible to damage are the Pulse Forming Network (PFN) capacitors, and the thyratron switch. A substantial amount of damage occurs at the anode when the thyratron is subjected to inverse voltage. One study[1] reported that the power dissipated on the tube anode varies as the square of the peak inverse voltage and that the anode "hole drilling" occurs in the approximately first 50 nanoseconds (ns) of inverse.

The large MW tubes with their lower gas pressure and commensurately longer fall of anode potential, are particularly susceptible to inverse dissipation. Voltage reversal can severely damage high energy density pulse capacitors. Life expectancy of a capacitor will decrease by a factor of 2 with only a 30 percent voltage reversal. It has been shown that in a thyratron line-type modulator the inverse voltage will be as much as 1.5 times the initial PFN voltage in the worst case of a shorted load.[2] On the other hand it is customary to design the modulator with a load impedance slightly smaller than the network impedance to produce a small negative voltage on the thyratron. The approach is to apply just enough inverse to allow the thyratron sufficient time to recover and at the same time, prevent large inverse voltages from occurring.

The most effective protection technique is the end of line (matched) clipper. A schematic of the matched end of line clipper is shown in Figure 1. The circuit consists of a diode stack and a resistive load where the resistive load is chosen equal in magnitude to the network impedance. The choice of the diode stack depends on the following factors:

a. worst case forward current
b. worst case inverse voltage
c. power dissipation
d. diode recovery

Forward Current

It was decided that parallel operation of diodes was inadvisable as the ballast resistors needed to insure proper current sharing would be impractical at the tens of kA level. The alternative was to try to find a single diode capable of handling the worst case current. For a matched clipper diode the maximum current would occur if both the modulator load R_L and the clipper load R_c were shorted. The currrent would be

$$I_p = \frac{epy}{[Zo]} \qquad (1)$$

where epy is forward anode voltage, and [Zo] magnitude of PFN impedance.

For an epy of 40 kV and a [Zo] of 1 ohm, the peak clipper current would be 40 kA. Ignoring higher order current reflections the diode chosen must be capable of sustaining 40 kA for 10 μs pulse. Our diode selection began with destructively testing diodes of different average current ratings to find if this rating would relate to its peak current handling capacity.

The test consisted of pulsing individual off-the-shelf diodes at a given current level with a 10μs pulse repeated every 5 seconds for 10 shots. After checking the diode the current was increased to its next level usually in 1 kA steps. The results are shown in Figure 2. From the best-fit-line a diode with an average current rating of greater than 75 A would be required to survive a 40 kA pulse.

Worst Case Inverse Voltage

The next most important factor is the maximum reverse voltage (epx) the stack will sustain under the worst conditions. This is when the modulator load becomes shorted and the clipper load opens. This voltage, epx, has been shown to be as much as 1.5 times epy. For a charging voltage of 40 kV the "diode" would be capable of sustaining a reverse voltage greater than 60 kV. Of course there is no one solid state diode capable of meeting this need therefore a series stack of diodes is required.

Ideally, enough diodes can be connected in series where 60 diodes with 1 kV hold off could sustain a 60 kV voltage indefinitely. In practice the reverse leakage I_R and the junction capacitance Cs of individual diodes differ significantly. Both I_R and Cs are temperature and voltage dependent. Stacked diodes require both resistive and capacitance compensation to overcome individual variations. An equivalent circuit for the series stack is shown in Figure 3.

In this figure R_F is the equivalent forward resistance of the diode, R_R is the resistance equivalent to the leakage resistance, Cs is the diode junction capacitance and C_G is the diode capacitance to ground. In our design the worst case diode leakage (T = 200°C) was 15 milliamperes (mA) at 1 kV. A resistor equivalent to 1/2 this value was selected to parallel each diode. The worst case voltage division would then divide as V_1 = 870, V_2 = 1130. Without resistive compensation the voltage would divide as V_1 = 462V and V_2 = 1538 V.

The diodes are rated at 1000 volts (V) reverse with a maximum instantaneous peak reverse voltage of 1300 V. With resistive compensation the diode would survive, however, it would fail without it.

The diode junction capacitance and stray capacitance affect the voltage division whenever the voltage rises or falls. The junction capacitance can change significantly from diode to diode. A recent article[3] stated for one type of high power rectifier the reverse recovered charge Qrr stored in the junction while it passes from forward to reverse bias, can vary by more than 300 percent. For diodes with different values of Qrr the shunting capacitors provide a current path for the stored charge to dissipate. Additionally, the external shunt capacitance must be chosen large enough to swamp out all values of junction capacitance. In the case of our clipper stack the shunt capacitor was chosen to be 100 times the typical device junction capacitance when measured at 10 V.

Power Dissipation - Worst Case

The power dissipation of the individual stack diodes is important to the determination of the cooling required. The "worst case" philosophy was used in designing the stack mounting.

In the MW modulator the "worst case" conditions which would affect the diode dissipation are:

Shorted load, system shut-down time is 16 milliseconds (ms)

epx = 40 kV PIV

Ip = 20,000 A

t_o - 10 μs pulse width

prr = 125 pps

The forward power loss per diode is[4]:

$$P_{fwd} = Eo\, I_{av} + I^2\, rmsR \tag{2}$$

where

P_{fwd} is forward power loss per diode

E_o and R are emperical constants representative of the diode selected

I_{av} is average current in the forward direction, and

I^2rms is the root-mean-square forward current through the diode

The diode chosen for the MW modulator was the 1N4594 which had an E_o of 0.825 and R of 0.0008. For the case of the shorted load the average current, I_{avg} is:

$$I_{avg} = Ip \frac{to}{T} \tag{3}$$

where

to, pulse width is 10 μs,

Ip is the peak current, 20 kA, and

T is the pulse period, 8 ms

I_{avg} = 25 A and the square of rms current, I^2rms, is:

$$I^2rms = Ip^2 \frac{to}{T} \tag{4}$$

$$I^2rms = 5 \times 10^5 \text{ A}^2$$

Then the forward power loss per diode is:

$$P_{fwd} = 0.825 \times 25 + 5 \times 10^5 \times 0.0008$$

or

P_{fwd} = 420 W in the case of a shorted load

where the modulator will be operating for 16 ms (2 pulses).

According to the manufacturer this forward power dissipation is equivalent to an average sinusoidal forward current of 380 A which is comparable to maximum power dissipation of 560 W. For sinusoidal operation the peak power to average power dissipation is 3.14;[5] therefore the maximum (sinusoidal) peak power capacity of the modulator clipper diode is

$$560 \times 3.14 = 1758 \text{ W}$$

This is a sinusoidal equivalent to the individual diode power dissipated when conducting 20 kA for a 10 μs pulse operating at 125 hertz (Hz) rate for 2 pulses.

To verify if the chosen diode can handle this peak power, this value of 1758 W must be compared to the peak power diode heat dissipation.

The peak power in the diode produces a transient heating effect which if beyond the capacity of the diode to absorb or conduct this heat away, will destroy the unit. Again, the manufacturer provides curves of effective transfer thermal impedance for various operating times. At an ambient of 16°C and for 16 ms duration the junction to case thermal impedance is 0.09 maximum. Then the peak power that can be dissipated in the diode is limited by the maximum junction temperature of 200°C by the relationship[6]

$$P_{Peak} = \frac{200 - \text{Transient}}{r_{(t)}} \tag{5}$$

$$\text{Peak} = \frac{200 - 16}{0.09} = 2044\text{W}$$

Therefore, the diode selected for clipper operation meets the manufacturer's power handling requirements.

Power Dissipation - Normal Operation

The diodes ordinarily can dissipate 40 W each. The chosen diodes are designed to dissipate 40 W mounted in the stack in air. The normal operating

clipper current for each MW module is 8 kA. Each series stack of 60 diodes will have an average current of 5 A and an I^2rms of 2×10^4 A^2. Then the normal forward power per diode equals 20 W and the sinusoidal equivalent peak forward power would be close to 400 W. For air cooling of the diode stacks where the ambient temperature is 16°C, the diode manufacturer suggested 150 linear feet per minute through the stacks. The air flow requirement was factored into the modulator design.

Diode Recovery

The recovery of a forward-biased to a reverse-biased diode is a 2-fold process.[7] When a diode is suddenly reversed from the forward direction, the current will not immediately drop to its steady-state reverse-voltage value, I_s. It can only reach this value after the excess minority carriers are swept out of the junction, or recombine.[8] During this time the diode will conduct easily with a value determined by the external circuit impedance. Once the excess carriers are swept back across the junction, the diode voltage can begin to reverse and the diode current can drop. This period of time is called the storage time t_s.

The second part of the recovery process is called the transition time t_t, and this interval extends from the end of the storage time t_s, until the junction capacitance has been charged to the reversed-bias voltage.

Figure 5 shows the voltage and current waveforms illustrating these points. It has been shown that the storage time increases with larger forward currents; also larger reverse currents reduce storage time. A relationship expressing this is:

$$t_s = \tau \ln\left(1 + \frac{I_F}{I_R}\right) \qquad (6)$$

where τ is called the effective lifetime.

The transition time, t_t, is a function of the junction capacitance C_t and will be reduced by increasing reverse bias. According to 5(a) the estimate of t_t is $3R_LC_T$. When the capacitance is small the diode recovery can be low ns range.

A negative mis-match will cause a rapid voltage reversal on the end-of-line clipper diode stack. If the stack load were to be shorted or underdesigned then the combination of rapid voltage reversal and high reverse currents can destroy the diode stacks.[9]

Megawatt EOL Clipper Design

The clipper design chosen was based on a Westinghouse diode stack consisting of 20 each IN4594 diodes with a 30 K ohm, 10 W resistor and a 0.1 microfarad (μ F), 1 kV dc capacitor across each diode.

In the first design, the clipper diode assembly, Figure 6, consisted of 3 stacks in series. Each assembly had a mating one ohm clipper resistor in series. The one ohm clipper resistor had four Carborundum type number 890 SPIROLT resistors in a series parallel combination. Originally each diode-resistor assembly was designed to parallel each of the two module PFNs. Figure 6 shows the two assemblies for a MW module housed in a fiber glass-bakelite box. The end is removed to show the interior. With the end in place, the 3 fans forced approximately 750 cubic feet per minute of 15°C air into the box plenum. The air escaped through 4 centimeter (cm) diameter holes adjacent to individual diodes. The air velocity escaping all holes was greater than 200 linear feet per minute which surpassed the manufacturer's recommended limits. This design provided a non-repetitive inverse voltage safety factor of 2, an operating voltage; safety factor of 1.5 and a current safety factor of 4. It was thought that if one diode-resistor unit opened the other PFN unit could withstand the combined fault.

A second design used two diode stacks (cut into 4 sections of 10 diodes each) in series. The clipper load resistor consisted of eight Carborundum washer resistors (0.25 ohms each), type No. 916WSR25L, stacked in a series-parallel combination to give 0.5 ohms. A view of this EOL clipper assembly is shown in Figure 7. This unit has a non-repetitive voltage safety factor of 1.3 and a current safety factor of 2.

Performance of Clipper Circuits

Normal operation of the MW modulator at an epy of 10 kV is shown in Figure 8. The anode voltage fall and load current rise occur simultaneously. The clipper current trace was subject to pick-up during the main current pulse. Ignoring the false positive-going current signal, the clipper current is seen as a series of oscillations with a period equal to the PFN pulse width of 10 µs and a maximum peak of 500 A. The anode waveform suggests that the inverse voltage never exceeds 500 V. A theoretical verification of the clipper oscillations is found in Reference 1. The question of what happens when the clipper load shorts is shown in Figure 9. There is *no* noticeable change in anode voltage waveform. Actually the tube current waveform looks improved. The first three clipper current peaks increased with the second peak increasing more than the first. Comparing the second peak to the second clipper current peak in Figure 8 shows a 2.5 times increase when the clipper load is shorted. The waveforms of Figure 10 were taken with both the modulator load and the clipper load shorted. In Figure 10 the anode voltage waveform shows an inverse voltage of 1.5 kV occuring 20 µs after the tube current pulse. The peak clipper current is 8 kA for a epy of 10 kV. The peak tube current is 5 kA. The tube for this worst case does show some inverse conduction at the peak of the first clipper current oscillation. After this point the tube current always stays in the forward direction and the clipper diodes continue to pass high currents in an attempt to dissipate the energy stored in the PFN. Figure 11 shows the diode clipper stack voltage and current for both the main load and clipper load shorted. This figure shows a definite phase difference in the voltage and current waveforms. From the 20 kV trace, the diode voltage is 4 kV when the current is zero and the slope of current is 2.4×10^9. When the current is zero then the voltage must be inductive. The estimated inductance is:

$$V = L \frac{\Delta_i}{\Delta_t} \qquad (7)$$

$$L = \frac{4 \times 10^3}{2.4 \times 10^9} \sim 1.7 \text{ microhenries}(\mu H)$$

The individual diode package is the DO.8 which has a flexible stranded lead which is 0.660 cm in diameter and 6.86 cm long. A solid copper wire with the same number of circular mils has a diameter of 0.583 cm. The self-inductance of 60 diode leads can be calculated from[10]

$$L = 0.002\ell\ [\ell n \frac{4\ell}{d} - 3/4] \qquad (8)$$

where

ℓ = length of diode lead in cm,

d = lead diameter in cm, and

L = self-inductance of a diode in μh

$$L = 0.002 \times 6.86\ [\ell n \frac{4 \times 6.86}{0.583} - 3/4]$$

L = 0.042 μh per diode; then 60 diodes would have a self-inductance of 2.55 μH. This is fairly good agreement with the observed inductance.

Lastly compare a gas tube clipper, two 7890s in parallel, to the diode stack in Figure 12. The hydrogen filled triodes have inherently low inductance and could be thought to represent an ideal diode stack. The forward voltage drop of the gas tubes is only 1 kV peak while the diode stack has a 4000 V forward drop. For an epy of 10 kV with a shorted modulator load the gas clippers pass 10 kA peak which is what would be expected from a 0.5 ohm network and a clipper load of 0.5 ohm. The diode stack on the hand passes only 6 kA under the same conditions. The efficiency of the solid state diode stack can be improved.

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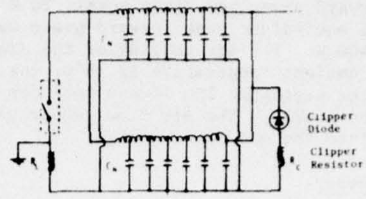


Figure 1. Modulator Circuit Showing EoL Clipper Circuit

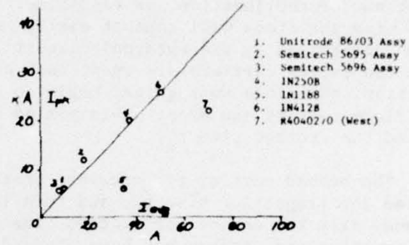


Figure 2. Peak 10 μs Pulse Current Resulting in Diode Failure Versus the Rated Diode Average Current for a Selection of Power Diodes. Diodes Pulsed Once Every 5 Seconds for 10 Shots Before Raising Current Level.

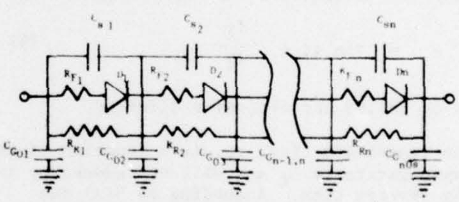


Figure 3. Equivalent Circuit for Diode Series String (diode lead inductance not shown)

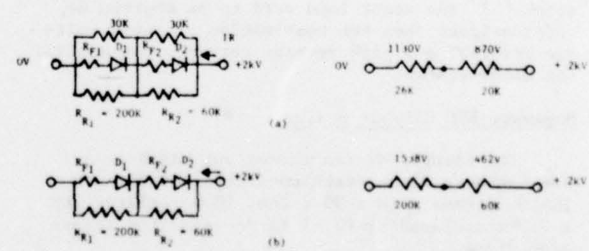


Figure 4. The Effect of Resistive Compensation on Voltage Distribution in a Two Diode Series String. (In (a) resistors were used while in (b) they were not.)

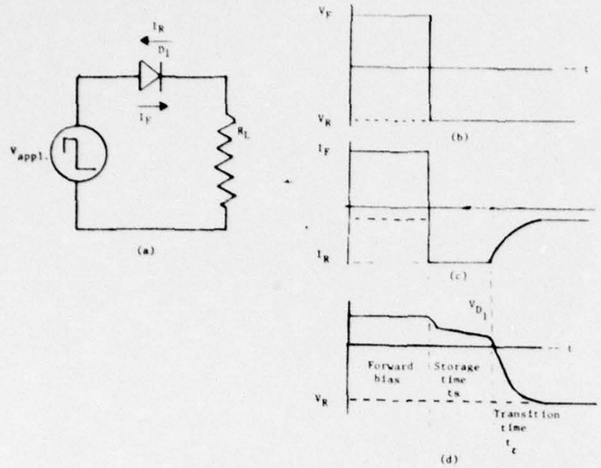


Figure 5. Stages of Diode Recovery: The waveforms shown in (b) is applied to circuit (a) with the resulting current (c) and diode voltage (d) waveforms.

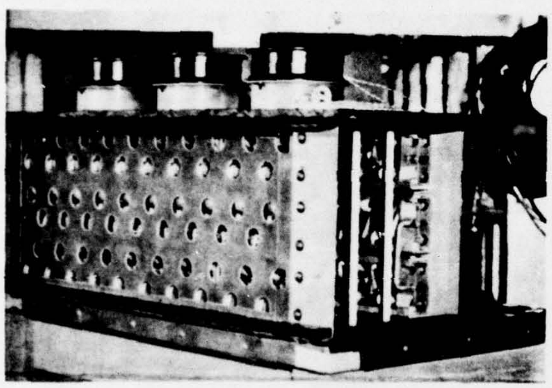


Figure 6. Original Megawatt Module EOL Clipper Diode Stacks and Housing

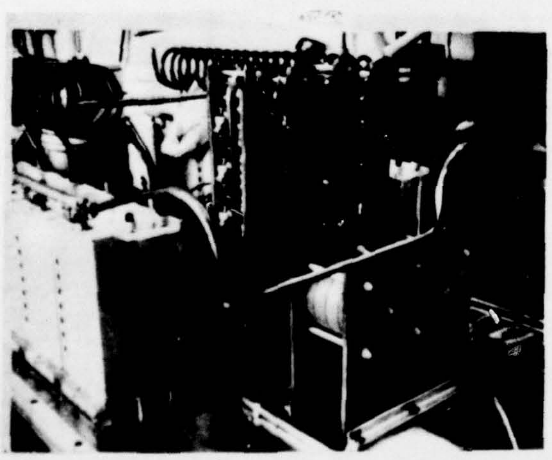


Figure 7. Other Megawatt Module with the 4 EOL Clipper Stacks, Clipper Load Connected to the Rear of the PFNs

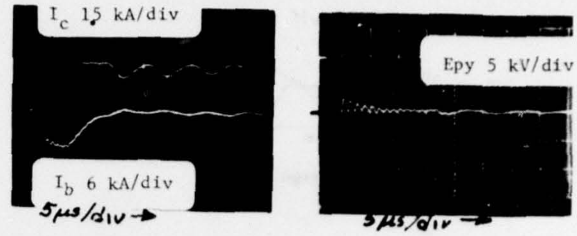


Figure 8. Normal Operation of the Modulator (R_c = 0.5Ω, R_L = 0.5Ω)

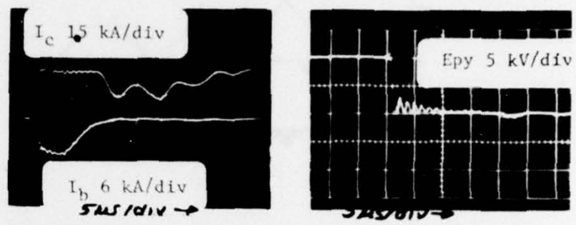


Figure 9. Modulator Operation with EOL Clipper Load Shorted (R_L = 0.5Ω)

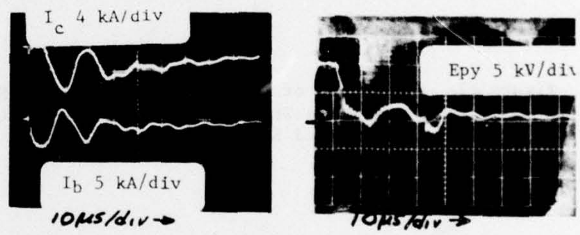
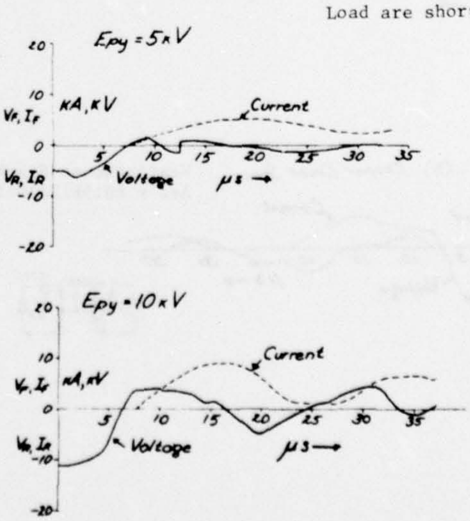
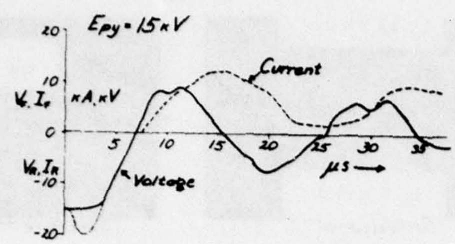


Figure 10. Modulator Operation with EOL Clipper Load and PFN Load Shorted

Figure 11. Solid State Diode Clipper Assembly Voltage and Current Waveforms at Various Epy: PFN Load and Clipper Load are shorted





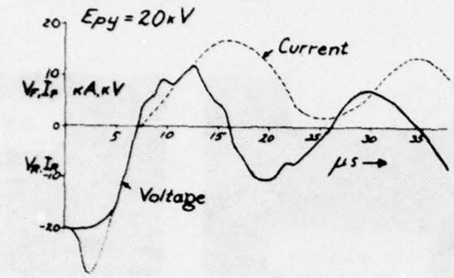


Figure 12. Comparison of Gas Tube Clipper and a Solid State Diode Stack at an Epy = 10 kV with the PFN Load Shorted.